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TRW

Highly Evolved Expendable Launch Vehicle (HEELV)

for the HRST Program

Final Report

Contract H27831D W-6-PP-02996

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Potential Cost Reduction by Highly Evolved Expendable Launch Vehicle Technology

Abstract

Multiple drivers, including consequences of successful United States policy and commercial pressures, have emerged for decreased space launch costs. This study evaluates the cost per pound to Low Earth Orbit (LEO) resulting from use of a range of expendable-launch-vehicle, first-stage, LOx/LH_2 concepts. The objectives of the Highly Reusable Space Transportation (HRST) program included an aggressive goal of \$300-\$400 per pound to Low Earth Orbit (LEO). To evaluate that goal, this study focused on how low the cost <u>can be</u> for very-low-cost expendable launch vehicles. Therefore, an overall approach consistent with commercial practices was assumed. It is recognized that use of present (exhaustive) development test philosophies and existing launch facilities could increase the costs significantly above those cited herein (Ref. 1). However, the expendable launch vehicle costs which are provided are felt to be achievable under the assumptions presented. A notional vehicle with a Gross Lift-Off Weight (GLOW) of about 542 Klbs, a sea-level thrust-to-weight ratio of 1.2, and a 107 Klbf second LOx/LH_2 stage engine was assumed in all cases. Metal tanks and structure were assumed except for one case. The notional vehicle baseline design used the TRW Low Cost Engine (LCE) concept which operated at low (~300 psia) pressure and used the stable pintle injector with an ablative chamber. The LCE engine was evaluated with metal and composite material structure and tanks. Other launch-vehicles first-stage engines (the F-1A, J-2, RL-10C, and the STME) were scaled to the notional vehicle thrust levels and the LEO costs per pound were evaluated. The data for the TRW low-cost engine were anchored by: 1) the recent fabrication of a complete pump-fed, 650 Klbf engine (including pintle injector, single-stage pumps (provided by Allied Signal), and ablative chamber); and 2) a prior, in-depth NASA study of low-cost launch vehicles and optimum production approaches. Available cost data were used as inputs for cost projections.

The study indicated that for the 25 Klb-class payloads, costs per pound to LEO were minimized at engine pressures and specific impulses of about 700 psia and 400 seconds, respectively, and rose very rapidly for pressures and specific impulses above about 1350 psia and 410 seconds, respectively. This behavior occurred due to the rapid increase in engine costs with increasing performance, which eliminated the benefits of increasing delivery capabilities. The low-pressure engine concept also enables the effective use of composites for vehicle structures and tanks and that combination led to the lowest cost per pound to LEO (~ $800/lb) of any system evaluated. Low costs depend critically on appropriate procurement and production and the study provides a discussion of potential approaches for those program elements.

It is hoped the enclosed data are of value to program planners in their attempts to define and provide competitive and capable United States launch vehicles.

Introduction and Background

The forerunners of today's space launch vehicles began in the early '50s with the development of the Atlas ICBM which was constrained by the requirements of a fixed-weight payload and a diameter of less than ten feet. This led to the general launch vehicle design concept of minimum weight and maximum propulsion performance which has, for the most part, persisted to this day. Based upon material and propulsion technologies of the 1950s, the design reflected the use of low pressurization of the propellant tanks (less than 30 psia) with minimum gage steel tanks (16 mils at the top of the tank). This, together with pump-fed engines, provided sufficient performance to achieve mission requirements. This design philosophy led to a relatively complex system with many design interfaces leading to labor-intensive fabrication, assembly, and testing operations further complicated by the program management involving prime, associate, and many sub-contractors. The great number of different contractors was influenced by both the complexity of the system design and government policy.

Military requirements for logistics, performance, and security were consistent with designing for maximum performance with optimum cost as a derived quantity. The payoff for increased performance was in increased net payload-to-orbit which was, for many pressing reasons, of higher priority than mission cost optimization. At present, there is an increasing commercial and government demand to reduce the overall cost of space launch. The present study is intended to show the application of design-for-minimum cost by considering the use of design simplicity leading to manufacturing and operational procedures which yield significant reductions in the dollars-per-pound to low-Earth-orbit (LEO) of less than one thousand dollars per pound to LEO including the amortization of DDT&E. The designs are restricted to vehicles with Gross Lift-Off Weights (GLOWs) of about 542 Klbs. and a thrust-to-weight ratio of 1.2 which results in first-stage, booster engine sea-level thrusts of 650 Klbf. Evaluations were conducted of first stages which used a variety of engine designs with chamber pressures ranging from 300 psia to 2,250 psia. One design involved the use of a pressure-fed engine with a 300 psia chamber pressure together with composite tanks and structures. The use of composites can be exploited for this design (Ref. 2) because, as will be shown, the significant reduction in structural factors outweighs the reduction in specific impulse to give a vehicle with the lowest dollars-per-pound to LEO over the use of higher-performing pump-fed systems, since these systems, operating at <u>very low</u> tank pressure would use metal tanks and cannot exploit the maximum benefits of composite use. In every case, the upper stage of the two-stage rocket was assumed to use a 107 Klbf (vacuum) thrust level engine which operated at a chamber pressure of 300 psia with the TRW pintle injector concept.

While the Low Cost Engine (LCE) is the key element in the design of the low cost expendable launch vehicles for this study, the entire concept of the LCLV has its basis in the 1969 NASA study (see Ref. 3). At the request of the NASA Administrator (James Webb), this study was undertaken to determine the reduction in cost of expendable launch vehicles through the use of simplified design and operation processes. The resulting concept was based on findings that primary cost drivers are driven by the complexity of the vehicle in terms of the number of parts and interfaces, and not the size (or weights) of the parts. Complexity (developmental and operational risk) of performance-driven designs results in a near-exponential increase in staffing and tends to overwhelm the nearly linear increases in material and propellant cost of simpler designs. For the design-for-minimum cost approach the design, manufacture, and operation of the system is based on doing what is considered necessary to achieve IOC without regard to general government and industry specifications or practices. This approach of simplicity is believed to lead to low cost consistent with high reliability.

Performance Considerations

For purposes of this study, a baseline vehicle is considered which uses the TRW pintle engine design for the first and second stages. The thrust for the first stage (booster) engine is 650,000 lbs. (sea level) and the thrust of the second stage (sustainer) engine is 107,000 lbs. The thrust-to-weight ratio, at sea level, is held constant at 1.2. Aluminum tanks and structure are used for both stages with LOx/LH_2 propellants in both stages. Figure 1 shows the performance parameters and estimated weight breakdowns for delivering approximately 25,000 lbs. of payload to a 100 n.mi. (LEO) orbit using a true-East launch from the Cape. For comparison purposes, variations in the configuration will only include changes in the booster engine by replacing the baseline engine with several engines with increasing chamber pressures from 300 psia to 2250 psia to show the increase in payload to LEO. All configurations which assume metal tanks and structure were assumed to use pump-fed engines, with the complexity and cost of the pumps matched to the specific engine needs. A final configuration was considered which used composite tanks combined with the use of low (300 psia) chamber pressure engines in both stages with pressure-fed systems.

The tradeoff to be considered will be the cost per pound delivered to LEO as a function of booster engine performance. It is recognized that cost projections are inevitably somewhat judgmental and relevant booster engine cost data have been used as available. The estimates of the costs of the TRW low-pressure engine are anchored by the recent experiences of design and build (in less than one year) of a complete LCE (Figure 2) including the chamber, ablatives, and single-stage pumps (supplied by Allied Signal). Overall approaches assumed for the LCE are summarized in Table 1.

	Wt (lb)
GLOW	541,667
Payload Wt	25,554
Payload Fairing Wt	2,300
Stage 2	
Stage 2 Wet Wt	74,114
Stage 2 Dry Wt	8,105
Structure	5,096
Sec. Struct.	368
Propulsion System	1,425
Main Engine	850
Plumbing	575
Avionics	670
Thermal Control	368
Misc.	178
Propellant	66,009
Main Impulse	65,562
Residual	487
Engine Characteristics	
Number	1
Vac. Thrust (lb)	107,000
Vac. Isp (sec)	423
Chamber Press. (psi)	300
Burn Time (sec)	259
Stage 1	
Stage 1 Wet Wt	439,699
Stage 1 Dry Wt	49,473
Structure	29,241
Sec. Struct.	2,238
Propulsion System	13,192
Main Engiens	5,000
Plumbing	8,192
Avionics	1,699
Thermal Control	1,712
Misc.	1,391
Propellant	390,226
Main Impulse	386,176
Residual	4,050
Engine Characteristics	
Number	1
Vac. Thrust (lb)	803,000
Vac. Isp (sec)	415
Chamber Press. (psi)	700
Burn Time (sec)	200

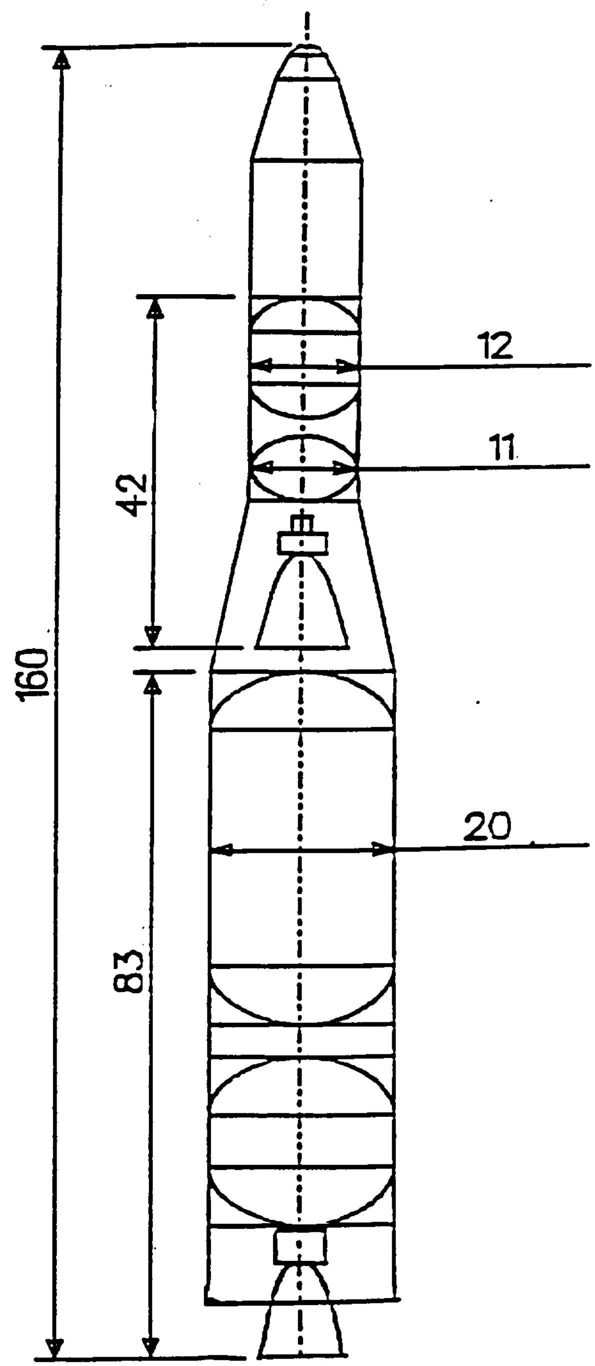

Figure 1. Structure Stabilized LOX/LH2 with Low Pressure Engines (107 Klb Thrust Upper Stage) (Baseline)

Table 1. Approaches for Low-Cost Expendable Launch Vehicles

- **Simple monocoque or low-cost composite structures instead of complicated honeycomb, isogrid, etc.**
- **Low engine operating pressures (300-700 psia)**
- **Liquid propulsion two stages for earth-to-orbit launcher**
- **Passive cooling using low cost, high durability ablative liners**
- **Pressure-fed systems or simple, single-stage, foil bearing, hydrodynamically lubricated and cooled pumps**
- **Minimized engine and system parts count, i.e., reduce parts count, by two orders of magnitude from that of the current engines**
- **Propulsion system simplification to minimize development though qualification costs**
- **Avoidance of combustion instabilities by design selection**
- **Simple gas generator engine cycle to drive pumps**

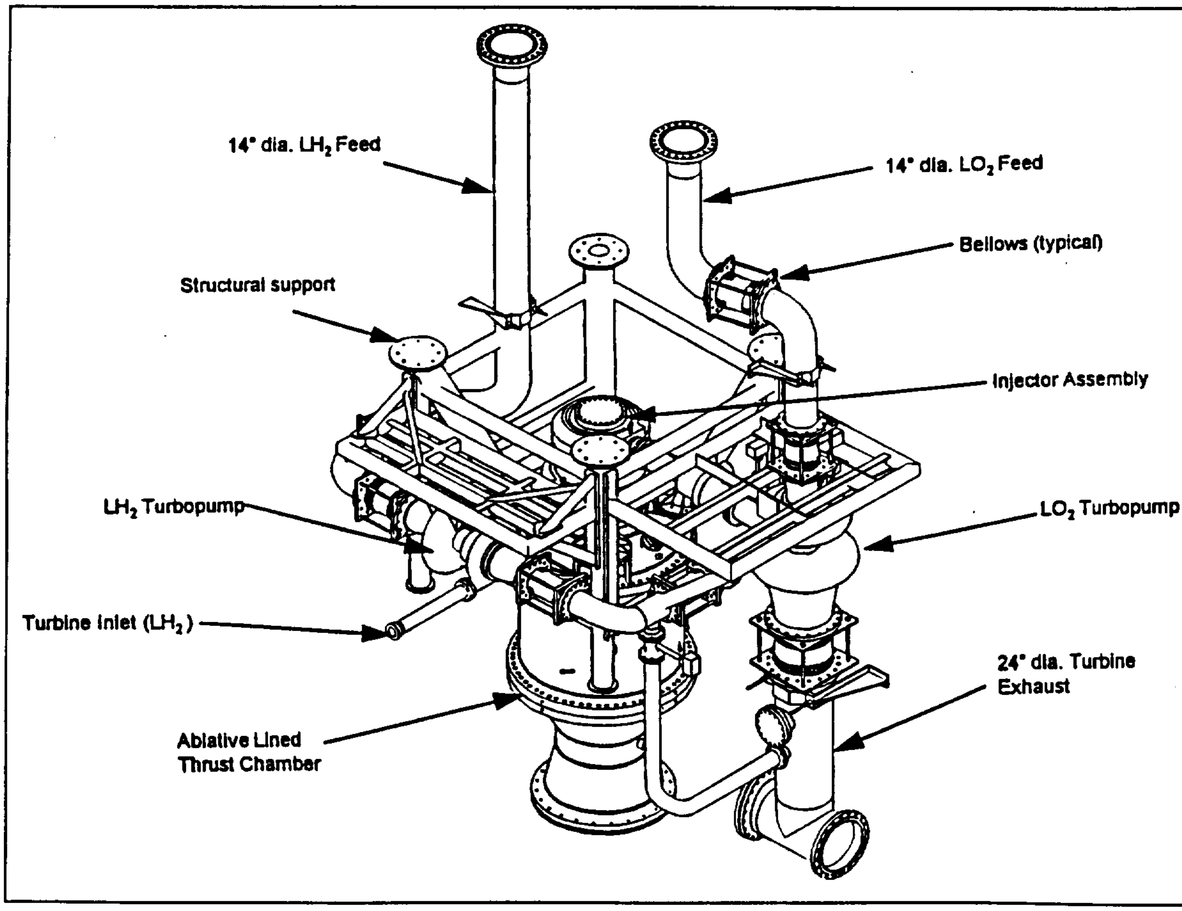

Figure 2. Low-Cost Engine (LCE)

As shown in Figure 3, there is a direct correlation on propulsion costs as a function of parts and interface counts and chamber pressure. The main cost driver for propulsion system costs is the operating chamber pressure, Pc. For chamber pressures below 1,000 psia, there is a wide range of options ranging from emphasis on minimum weight designs such as the F-1, J-2, and R-10 to the LCE which is designed for minimum cost with far fewer parts and interfaces compared to the previously mentioned designs. There is a wide range in development and recurring costs resulting from lower to higher labor efforts due to a wide variation in complexity. As one begins to strive for maximum performance by operating at chamber pressures well above 1,000 psia, for example, the STME at Pc = 2,250 psia and the SSME at Pc = 3,260 psia, the acceptable designs are restricted to a narrow band of highly complex and quite costly designs. Within a fixed chamber pressure design class, the recurring cost of an engine scales approximately as the square-root of the thrust level since the thrust is proportional to the throat area. In the case of varying the chamber pressure there is an exponential increase in the recurring cost of the engine at a fixed thrust level as the chamber pressure is increased beyond about 1,000 psia. Figure 3 is a plot of the heuristically-derived formula for the first engine cost, C (in millions of dollars) as a function of thrust level, F (in pounds) and chamber pressure, Pc (in psia) in 1995 dollars. The formula is expressed as

$$C = 2{,}000(F)^{0.5}\, e^{(Pc/850)}$$

In Figure 3, all engine thrust levels have been normalized to F = 500,000 pounds. This meant scaling F-1 down from 1,500,000 pounds, J-2 up from 250,000 pounds, French Vulcain up from 200,000 pounds, and RL-10 up from 30,000 pounds of thrust. The dashed curve represents the spread in cost of the various designs at the low pressure end of the spectrum to a near vanishing of the spread at the SSME level of Pc of 3,260 psia. Figure 4 is a plot of the LCE designs fixed at Pc = 300 psia for a thrust range from 40 Klbf to 1000 Klbf pounds. The design points are TRW design cost estimates. Using a 90% learning curve would yield an average unit cost of 0.5C for one hundred manufactured engines. Figure 5 shows the variation in first-engine costs for LCE ranging

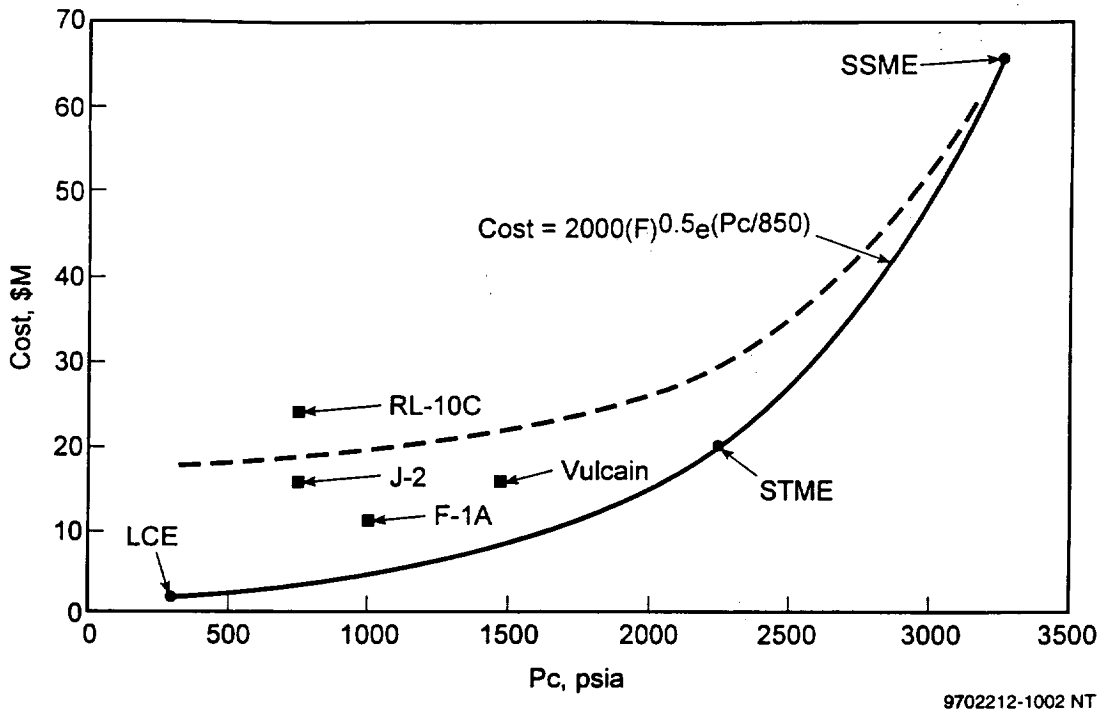

Figure 3. First Engine Costs (1995$) as a Function of Increasing Chamber Pressure for a Fixed thrust Level of 500,000 lbs

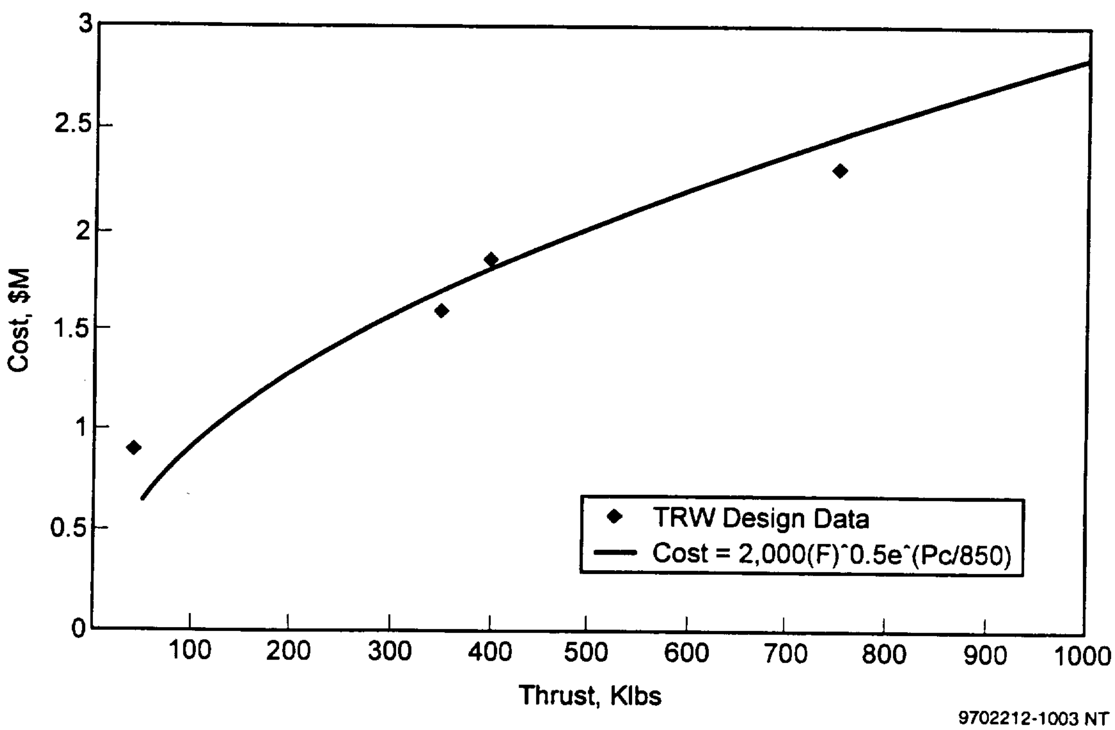

Figure 4. First Engine Costs (1995$) as a Function of Thrust for a Fixed Chamber Pressure of 300 psia

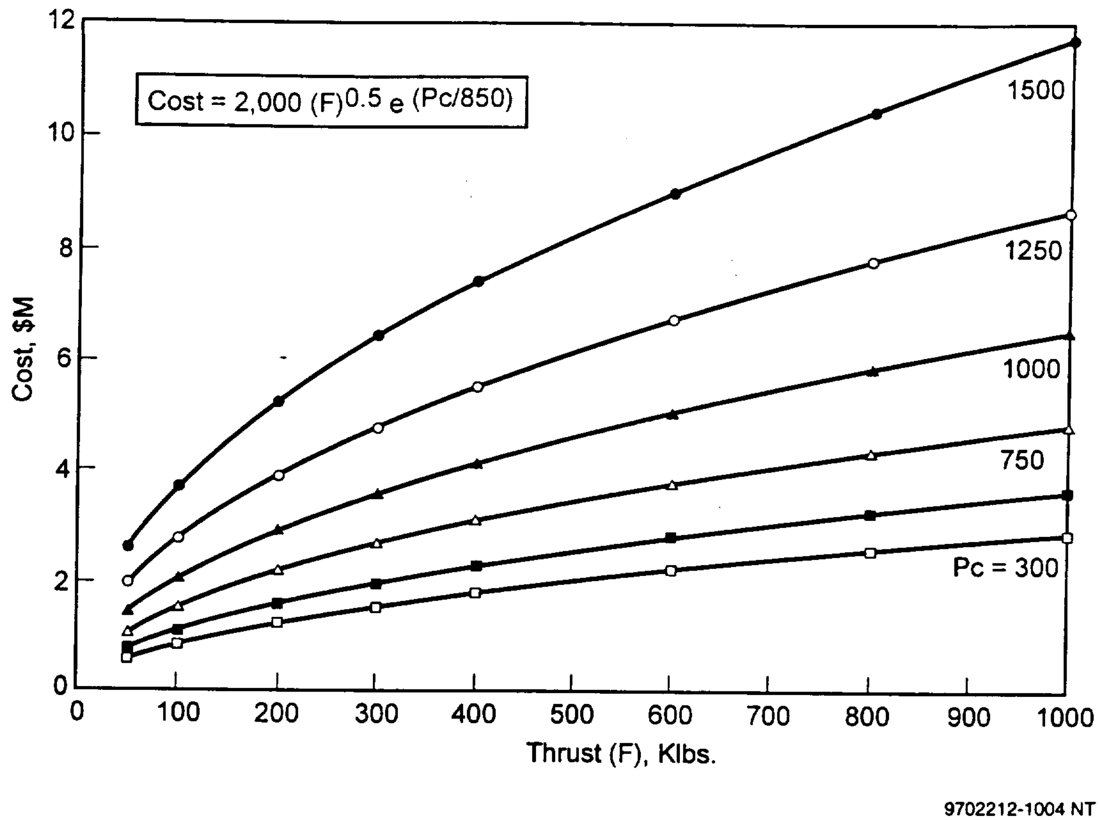

Figure 5. First Engine Costs (1995$) as a Function of Thrust for a Range of Chamber Pressure (pc = 300 psia to 1,500 psia)

in design thrust levels of 400 Klbf to 1000 Klbf pounds with chamber pressures increasing from 300 psia to 1,500 psia.

Using various booster engines to replace the baseline engine (with Pc = 700 psia), Table 2 shows the resulting payload capabilities of all the vehicles with a constant GLOW of 650,000 lbs. For the costing calculations to follow, the DDT&E for each booster engine is assumed to be 30 times the first unit cost (see Appendix A). The next section on costs describes the bases for the cost estimates of the baseline configuration and is followed by changes in DDT&E and booster engine costs which leads to varying dollars per pound to LEO for the various resulting launch vehicles.

Cost Analyses and Tradeoffs

The current, baseline launch vehicle is very similar to the design concept of the Low Cost Launch Vehicle (LCLV) studied for NASA in 1969 (Ref. 3), and the extensive design and cost studies for that effort provide useable data for development and recurring cost estimates for this effort. Labor and material acquisition for similar efforts can be converted to current year dollars by multiplying by a factor of four. This approach is realistic since LCLV uses design-for-minimum-cost rather than design for minimum weight and maximum performance. This approach leads to simplified (less complex) hardware with reduced development, testing, and manufacturing processes. This then leads to less intensive operational efforts. A major assumption in the following cost estimates is that the program starts from a full acquisition of facilities which can have costs reduced by using some existing facilities.

The overall costs of the launch vehicle system consist of the sum of costs in the following categories:

- non-recurring costs, including DDT&E for the launch vehicle through its acceptance tests
- recurring costs, including fabrication, assembly, and checkout of the vehicle; launch operations; and recurring support activities. Some of these costs are subject to improvement on a learning curve and others are not.

All of the costs can be normalized in terms of the first engine recurring cost FERC. The average recurring cost per unit decreases with the number of manufactured units, N, according to a learning curve which is defined as the average cost of 2N unitsdivided by the average cost of N units. For a 90% learning curve, and total productions of 25 and 100 engines, the average engine recurring costs (AERC) are 0.61C and 0.5C, respectively. Other recurring costs such as ground support and propellant costs would be subjected to a somewhat higher learning curve. The non-recurring costs can be represented as a multiple of the first unit cost, if desired.

Table 2. Payload-to-LEO versus Different Booster Engine Assumptions for Constant GLOW

- Sea-level thrust is 650,000 lbf
- GLOW = 541,667 lb.
- 28° Azimuth, 100 n.mi. circular orbit
- LCE-type engine, 2nd stage Pc = 300 psia
- Vehicle type: LCLV
- DDT&E amortized over 25 and 100 flights (90%) learning curve
- DDT&E for booster engines assumed 30 times first unit cost
- STME, Pc = 2,250 psia, Payload = 29,279 lb.
- EELV, Pc = 1,350 psia, Payload = 28,022 lb.
- ULCE, Pc = 700 psia, Payload = 25,554 lb.
- ULCE, Pc = 300 psia, Payload = 22,682 lb.
- ULCE, Pc = 300 psia, Composite tank, Payload = 30,464 lb.

Table 3 shows a breakdown of the non-recurring costs for the baseline, expendable, two-stage vehicle (Figure 1). The mass fractions of stages one and two are each 0.12. The total non-recurring cost is estimated to be $600M and will be assumed to be amortized over a procurement of 100 units. Table 4 shows a breakdown of the recurring costs which result in an average cost per launch of $25M ('95 dollars) and which includes amortization of the development, production, and ground and launch support costs. For the 25,000 lbs. payload, this gives a cost-to-orbit of about $1,000 per pound. A production learning curve of 90% has been assumed which yields an average engine recurring cost (AERC) of 0.5 FERC.

Table 3. Breakdown of DDT&E Costs ('95 Dollars)

• Development Cost of Engines	1st Stage	$110M
	2nd Stage	28M
• Structure	1st Stage	70M
	2nd Stage	36M
• Astrionics	1st Stage	28M
	2nd Stage	54M
• Stage Integration	1st Stage	70M
	2nd Stage	45M
• Management, Fee, etc.	1st Stage	94M
	2nd Stage	65M
• Plant and Tooling* – 106M		
• Ground Support Facilities* – 143M		
Total Non-Recurring (DDT&E)		600M

*Note: Plant, tooling, and ground facilities cost of $249M would be reduced by available facilities and are not included in DDT&E.

Table 4. Recurring Costs (No Reuse, '95 Dollars, 90% Learning)

Cost Element	$M
• Non-Recurring Costs (DDT&E)	600.0
• Production Only	9.5
• Non-Recurring (Amort. Over 100 Units	6.0
• Ground and Launch Support	9.5
• Average Cost Per Launch (100 Launches, Incl. Amort.)	25.0

Production (Incl. Integ)	
Propulsion	2.1
Structures	1.1
Astrionics	1.8
Stage Integ.	2.8
Management, Fee	1.7
	9.5

Ground & Launch Support	
Assem., Chk., Launch	1.5
AGE&MGE Equip. Maint.	3.0
Range Support	0.7
Mission Cont., Fueling	2.8
Base Support	0.5
Management, Fee	1.0
	9.5

The importance of this very approximate exercise is to show the methodology to be used. It must be pointed out, as shown in Tables 3 and 4, that all cost elements have been included together with amortization of the non-recurring costs (excluding costs for plant, tooling, and ground support facilities.)

Table 5 summarizes the DDT&E and recurring costs for launch vehicles using the various booster engine choices including the assumption that each booster engine is developed from scratch with an engine development cost of 30 times first unit cost. Using the payload-to-LEO results from Table 2, the costs per pound to LEO are shown for each launch vehicle in Table 6 and in Figure 6.

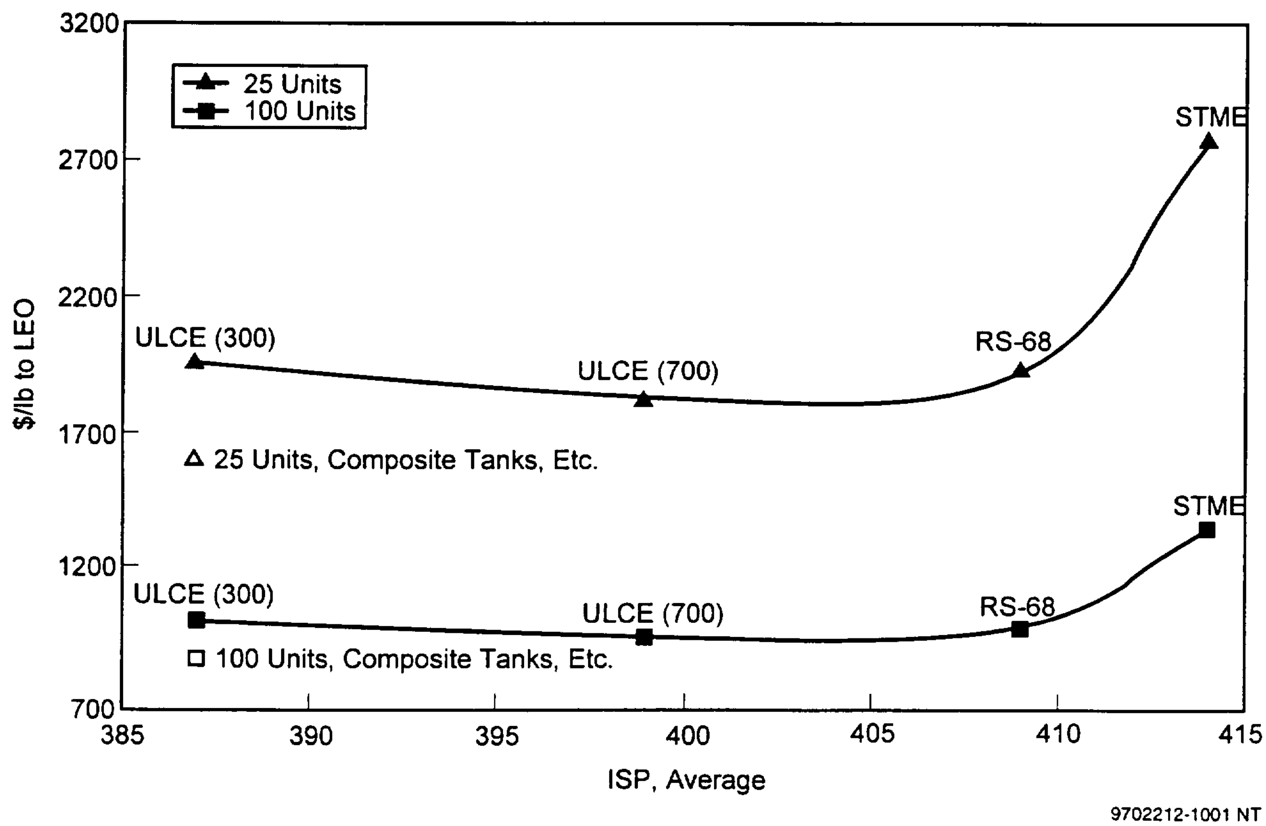

Figure 6. Cost/lb to LEO versus Average I_{sp} (LOX/H_2)

Table 5. Launch Vehicle Cost Data for Various Booster Engines

Engine (Pc)	Total DDT&E	Recurring (100 units)	Recurring (25 units)
LCE (300	$558,700,000	$23,897,000	$44,688,000
LCE (700)	600,000,000	25,000,000	47,180,000
RS 68 (1,350)	726,700,000	28,377,000	54,818,000
STME (2,250)	1,172800,000	40,268,000	81,732,000
LCE (300)* (composite)	658,700,000	24,897,000	48,688,000

*$100,000,000 added to DDT&E for composite development.

Table 6. Costs per Pound to LEO

Engine (Pc)	LEO Payload (lbs.)	$/lb. (100 launches)	$/lb. (25 launches)
LCE (300)	22,682	1,054	1,970
LCE (700)	25,554	938	1,846
RS68 (1,350)	28,022	1,012	1,956
STME (2,250)	29,279	1,375	2,791
LCE (300) (composite)	30,464	817	1,598

The average I_{sp} is used as a point of reference and is obtained by adding the sea-level I_{sp} to the vacuum I_{sp} of the booster. This is then divided by two and the result is added to the vacuum I_{sp} of the upper-stage engine and that result divided by two. This single value used in the ideal rocket equation, together with losses, gives accurate results when compared to actual flight runs on a computer. From these results it can be seen that the use of composites can be exploited by pressure-fed systems since tank pressures of 400 psia, as used in the present composite design, yield lightweight structures. High performance pump-fed systems cannot exploit the use of composite tanks because tank pressures of about 50 psia (typical) would use metal tanks which also give wall stability compared to low-pressure composite tanks.

Figure 7 shows the weight estimates for the composite design yielding a payload-to-LEO of 30,464 lbs. The mass fraction (or structure factor) of each stage is a little over 0.08, as compared to the baseline of about 0.12. A calculus of variations derivation (see Appendix B) shows that the exchange ratio of $\pm$ 1 second of I_{sp} is balanced by $\pm$ 0.0012 for structural factor. For the case of the 300 psia engine compared to the 700 psia engine, a deficit of about 12 seconds in I_{sp} can be balanced by a decrease in structural factor of 0.014 which is more than satisfied by going from 0.12 to 0.08. Note that the dimensions on vehicle size on Figures 1 and 6 are approximate. The overall cost estimates require production and procurement procedures which contribute to the overall low cost of the Low Cost Expendable Launch Vehicle concept. The next section is a description of this process.

Production and Procurement

One of the reasons for the high cost of current launch vehicles (LV) is believed to be the large number of widely separated airframe manufacturers involved, with multiple checkout procedures and inspections required to assure compatibility. The present concept is based on a single airframe/assembly/integration plant, designated "Plant A," located at or near the launch site, where 90% of the hardware fabrication and the stage assembly and integration are accomplished, and the fully assembled stages are checked out before delivery.

Raw materials and purchased parts flow into the factory, and the finished stages are transported by rail car or crane to a vehicle assembly building (VAB) for LV assembly, payload integration, and prelaunch checkout. The LV/ML (mobile launcher) are then transported to the launch pad by a crawler/transporter for final checkout, countdown, and launching.

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One of the reasons for the high cost of current launch vehicles (LV) is believed to be the large number of widely separated airframe manufacturers involved, with multiple checkout procedures and inspections required to assure compatibility. The present concept is based on a single airframe/assembly/integration plant, designated "Plant A," located at or near the launch site, where 90% of the hardware fabrication and the stage assembly and integration are accomplished, and the fully assembled stages are checked out before delivery.

Raw materials and purchased parts flow into the factory, and the finished stages are transported by rail car or crane to a vehicle assembly building (VAB) for LV assembly, payload integration, and prelaunch checkout. The LV/ML (mobile launcher) are then transported to the launch pad by a crawler/transporter for final checkout, countdown, and launching.

	Wt (lb)
GLOW	541,667
Payload Wt	30,464
Payload Fairing Wt	2,300
Stage 2	
Stage 2 Wet Wt	68,357
Stage 2 Dry Wt	5,255
Structure	2,364
Sec. Struct.	250
Propulsion System	1,425
Main Engine	850
Plumbing	575
Avionics	670
Thermal Control	368
Misc.	178
Propellant	63,102
Main Impulse	62,615
Residual	487
Engine Characteristics	
Number	1
Vac. Thrust (lb)	107,000
Vac. Isp (sec)	423
Chamber Press. (psi)	300
Burn Time (sec)	248
Stage 1	
Stage 1 Wet Wt	440,546
Stage 1 Dry Wt	32,515
Structure	13,613
Sec. Struct.	2,000
Propulsion System	12,100
Main Engiens	5,400
Plumbing	6,700
Avionics	1,699
Thermal Control	1,712
Misc.	1,391
Propellant	410,844
Main Impulse	406,794
Residual	4,050
Engine Characteristics	
Number	1
Vac. Thrust (lb)	866,800
Vac. Isp (sec)	400
Chamber Press. (psi)	320
Burn Time (sec)	188

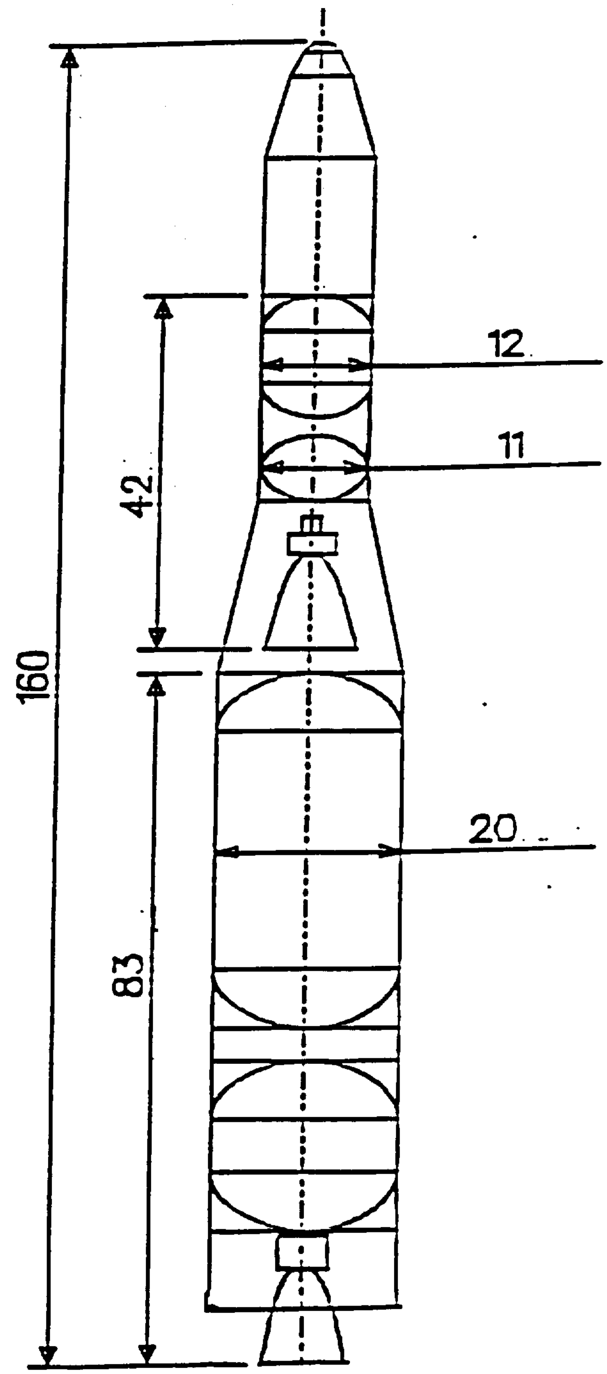

Figure 7. Structure Stabilized LOX/LH2 with Low Pressure Engines (107 Klb Thrust Upper Stage) (Composite)

LV Production in Plant A

The concept of LV simplicity and conservative design margins leads to a low-cost vehicle about the size of an EELV. The concept of a factory (Plant A) adjacent to the launch site is consistent with the vehicle characteristics and leads to simplicity in manufacture, transport, and launch support operation. The plant is specially designed to facilitate the fabrication of tanks, engines, and interstage structures, and the integration of these with purchased parts to complete the launch vehicles.

The concept of management of the factory and launch support activities (see Table 7) encompasses efficient modes of production, procurement, integration, and checkout, with emphasis on quality assurance and effective customer service, from standardized software to vehicle checkout and launch support.

Table 7. Production and Procurement

Plant A	Located within a few miles of launch pad for easy transport by waterway to the launch pad
Plant Management	
Procurement of raw materials and purchased parts	
Fabrication techniques -- metal forming and welding, machining of injectors and other parts	
Purchased Parts -- components and small subsystems	
Assembly and integration of stages or complete LV	
Quality assurance of in-house work and purchased parts	
Final checkout of LV – in factory and at launch site.	

Alternate Sites for Plant A

If Plant A can be located within a few miles of the launch site, rail transport can be used for moving the stages or vehicles to the base, where they are erected in readiness for payload integration and final checkout before launch. If space were unavailable adjacent to the launch site, a barge would be required, terminated by rail transport from the barge dock to the erection point. In many respects, the most convenient location for Plant A would be directly adjacent to the VAB, permitting crane transport (rather than rail) of stages from factory to the vehicle assembly bays, and near the launch control center (LCC) for routine stage checkout. While this location would eliminate preparation of a completely new site, barge dock, rail line, etc., and would simplify the stage transport and checkout operations, possible disadvantages such as pad clearance and interference during the plant construction period should be investigated. Plant A requires a 30-to-50 acre site with a plant size of 400 ft. by 900 ft. This will allow the concurrent production of three launch vehicles on a continuous basis.

Plant A Layout and Work Flow

The Plant A layout is designed to provide for convenient handling of raw materials and purchased parts, from the receiving through processing and integration into complete launch vehicles, all under one roof. Some of the layout considerations are listed in Table 8.

Table 8. Plant A Layout and Facilities

- Barge dock, rail dock, and truck receiving
- Materials handling equipment (metal plate, purchased parts, etc.)
- Receiving inspection and storage
- Metal cutting, forming, welding, etc.
- Jigs, tools, and other facilities
- Smooth flow of work to assembly line
- Stage buildup and integration
- Quality control inspections throughout processing and assembly
- Rail transport of completed stages and/or assembled LVs
- Final factory checkout of stages and/or assembled LVs
- Office space, restrooms, restaurant, and recreation areas
- Grounds layout, rail to VAB, parking space, and security

Work flow will proceed through Plant A according to the following outline:

- Delivery of Raw Materials and Purchased Parts
  - Mill runs of metal plate – size and thickness
    - Delivered on palettes by barge, rail, or truck
  - Purchased parts and subsystems
    - Delivered in boxes or crates by rail or truck
- Receiving Operations
  - Handling of raw materials – crane, tractor, or dolly
  - Receiving inspection of raw materials and purchased parts
    - Mark all stock for traceability
  - Sample and functional tests to prove quality – acceptance
  - Storage for convenient access when needed
- Raw Materials Handling
  - Remove from storage – clean and inspect before processing
  - Cutting – shear, torch, or saw – template check
  - Forming plates – brake or roll – check shape
  - Machined parts – lathe, mill, shape, drill – inspect
- Welding Assembly
  - Jig-mounted plates and machined parts assure mating
  - Continuous inspection of welds – repair flaws at once
  - Cleanup and approval of sub-assemblies before mating
- Sub-assembly Lines Leading to Stage Assembly
  - Mate and join tanks and engine shell
  - Add proof test components – hydrostatic proof test (horizontal)
  - Proceed to cleanup or correct leak if necessary
  - Clean up welded assembly after proof test
  - Paint or other protective coating
  - Add components and subsystems to completed stage
  - Add interstage structure
- Stage Checkout Operations
  - Electrical tie to LCC automatic checkout procedures
  - Final inspection – approval for delivery
- Stage Transport to VAB (or storage) in Horizontal Mode
  - Stage erection and LV/PL integration

Quality Assurance in LV Program

The fabrication of tanks and engines for the LV can be described as a combination of standardized boiler shop and shipyard practice for forming and welding the steel tanks and aluminum alloy interstage structures. Many test specimens of small tanks and engines have been produced in this way with simple tooling and at moderate cost. Despite numerous obvious imperfections in these early specimens, they have been found to be considerably stronger than the design values predicted. This experience gives assurance that expensive tooling and uncommon expertise are not required to assure satisfactory quality. Jigs and fixtures for the efficient handling and holding of work during cutting, forming, and welding are, of course, necessary. Such tooling will be planned and developed in a cost-effective manner, with quality assurance as the guideline. Proven methods will be used to prevent undue oxidation before welding and to control weld porosity. Materials and operational specifications will be developed to assure high quality in the final product with systematic sequencing of manufacturing operations and their quality verifications.

Provisions for continuous inspection of welds for flaw detection by ultrasonic techniques are assumed, with immediate correction of objectionable defects. Modern continuous x-ray inspection may be used for aluminum welds, but this method is believed to be less effective than ultrasonics for steel. Each tank will be hydrostatic tested for leaks after welding, to a proof pressure well above the normal operating conditions. Engines will be carefully inspected (not fired) to prove QA, but proper functioning of valves, gages, etc., will be thoroughly proven during the stage and vehicle checkout sequences.

Standard methods for inspection of raw material, purchased parts, and subsystems will be employed and catalogued in suitable manner for traceability. Appropriate inspection techniques will be used to check such parts during and after integration into stage assemblies.

Configuration management will be accomplished by means of essential but not elaborate specifications and procedures compatible with the low-cost vehicle concepts.

Production Milestones

The LV has been designed to facilitate a low cost/short time development program. Features have been selected which will be relatively easy to design and develop. Performance margins have been made conservative enough that extensive iterative testing should not be required to attain the level of performance and reliability required. Simplified methods of fabrication permit the construction of experimental hardware with simple tooling and minimum lead time; hence, the test program can get underway soon after go-ahead. It is expected that Plant A will be ready for production approximately fourteen months after site selection. First test flights will start two years after the functioning of Plant A with launch vehicle production proceeding four months later.

Conclusions and Recommendations

This study has attempted to show that a promising way to reduce the dollars per pound to LEO below $1,000 can be achieved. Very simple, low-pressure launch vehicle engines were assumed which should enable significant reduction in development costs from those usual for complex, high-performance engine concepts. Also, launch operation costs were assumed which were felt representative of a fully-commercial, and high rate, launch facility. The use of low-pressure engines combined with the judicious use of composites yields the lowest dollars-per-pound to LEO (~ $817) for this class of launch vehicles with a DDT&E cost considerably less than $1 Billion (i.e., estimated at $659 Million) and a recurring cost (for 100 vehicles) of less than $25 Million. Low-pressure engines operating at 300 and 700 psia, in combination with metal vehicles, resulted in costs per pound to LEO of about $1050 and $940, respectively. These estimates are partially anchored by the recent TRW experiences in design and build of a LCE within 12 months of go-ahead. The studied concept did not utilize recovery of any hardware, but the design of the first-stage with high pressure tanks and rugged engine design could lead to an easily-refurbished recoverable first-stage using metal tanks and maximizing impact robustness by sealing the engine with high pressure in the tanks during reentry which might lead to further cost benefits.

It is felt that the recommended design reflects a low cost, low risk concept and further detailed design, analyses, and testing should be undertaken to validate this very promising low-cost approach for access to space.

References

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2. Davis, Jr., J. G., "Materials and Structures for Low Technology Booster," NASA/LeRC (Presented at Workshop on Low-Cost Space Transportation Systems, OTA, Congress of the United States, Washington, D.C.), December 1, 1987.
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Appendix A. Engine Performance and Cost Data

Performance considerations are used to develop the following data as inputs to the final launch vehicle DDT&E and recurring cost estimates. The derived data are believed to be reasonable estimates of proposed or actual engines.

Pc (psia)	FERC ($K)	DDT&E ($K)	ε	Ivac (sec)
Booster Engines (650 Klbs, sea-level)				
300	2,295	68,848	8.5	400
700	3,674	110,220	15.8	415
1,350	7,893	236,793	19.1	419
2,250	22,756	683,670	22.5	422
Sustainer Engine (107 Klbs, vacuum)				
300	931	27,933	40.1	423

As noted previously, the engine DDT&E is 30 times the first engine recurring costs (FERC). For the case of 100 launch vehicles the average cost of each engine is 0.5 times the FERC and the DDT&E cost allocated to each launch vehicle recurring cost is 0.01 of the DDT&E cost.

Appendix B. Tradeoff Between Specific Impulse and Structure Factor

The ideal rocket equation can be used to estimate the tradeoff between specific impulse and structural factor to hold the velocity gain constant. Structural factor is defined as the ratio of the burnout weight (including residual propellants) of a stage divided by the initial weight of the fully loaded stage. The ideal rocket equation for the first stage is given by

$$v = Ig \ln r$$

where I is an average value of the sea level and vacuum specific impulse, g = 32.2 ft/sec., and r is the mass ratio given by

$$r = \frac{W_O}{\left(W_O - W_L\right)\gamma + W_L}$$

with W_O = Gross Lift-Off Weight (GLOW)

W_L = second stage (including the payload weight)

γ = first stage structural factor.

Defining W_O/W_L (payload ratio) as P we have:

$$v = Ig \ln \frac{P}{(P-1)\gamma + 1}$$

Taking the differential of v with respect to I and γ and setting dv = O (or no change in v), we have the following relation

$$dv = 0 = g\,dI \ln \frac{P}{(P-1)\gamma + 1} - Ig\,d\gamma \frac{P-1}{\left(P-1\right)\gamma + 1}$$

or

$$\frac{Id\gamma}{dI}=\frac{(P-1)\gamma+1}{P-1}\ln\frac{P}{(P-1)\gamma+1}$$

Using the following typical values:

$$P=4,\quad \gamma=0.1$$

we find $d\gamma/dI = 0.0012$ with I = 400 sec. This means that $\pm$ 1 sec. of I can be balanced by $\pm$ 0.0012 of γ. For this example, v = 14,476 ft/sec.